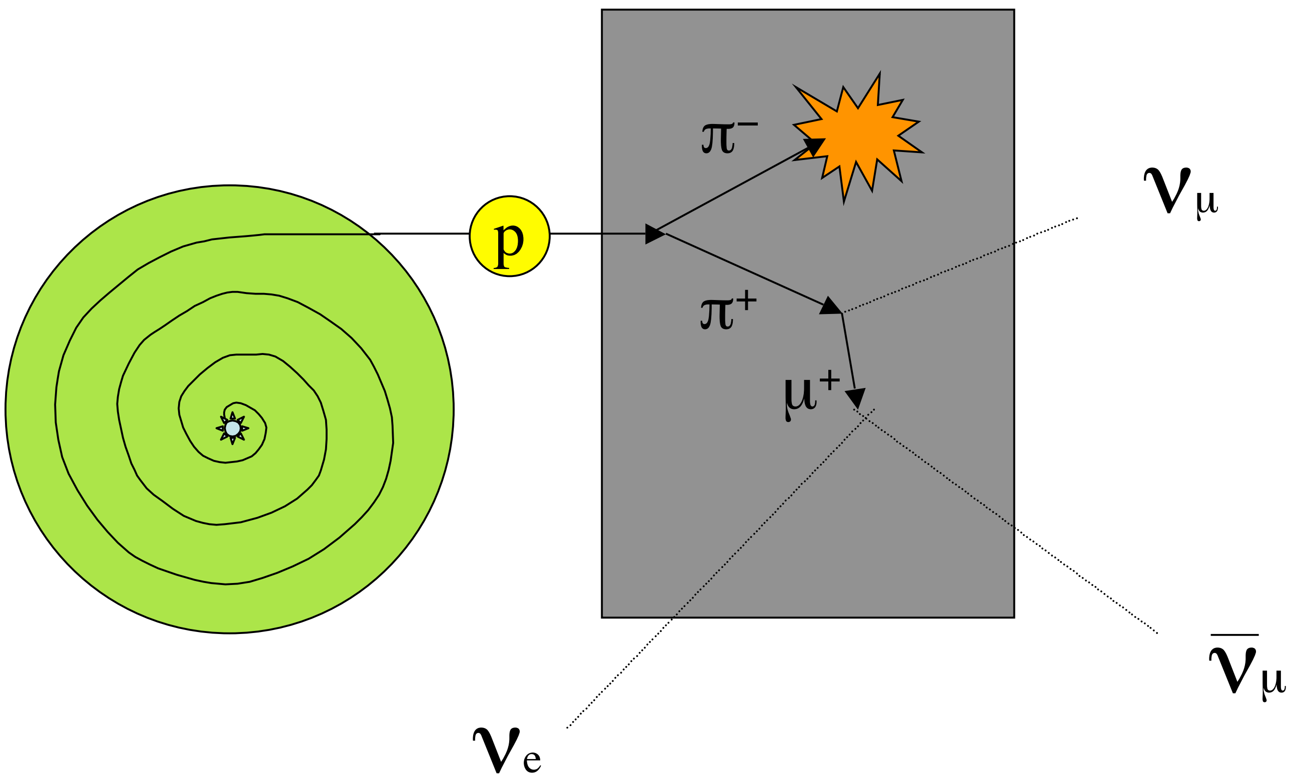
# DAEδALUS

SBL Workshop, Janet Conrad, MIT, May 14



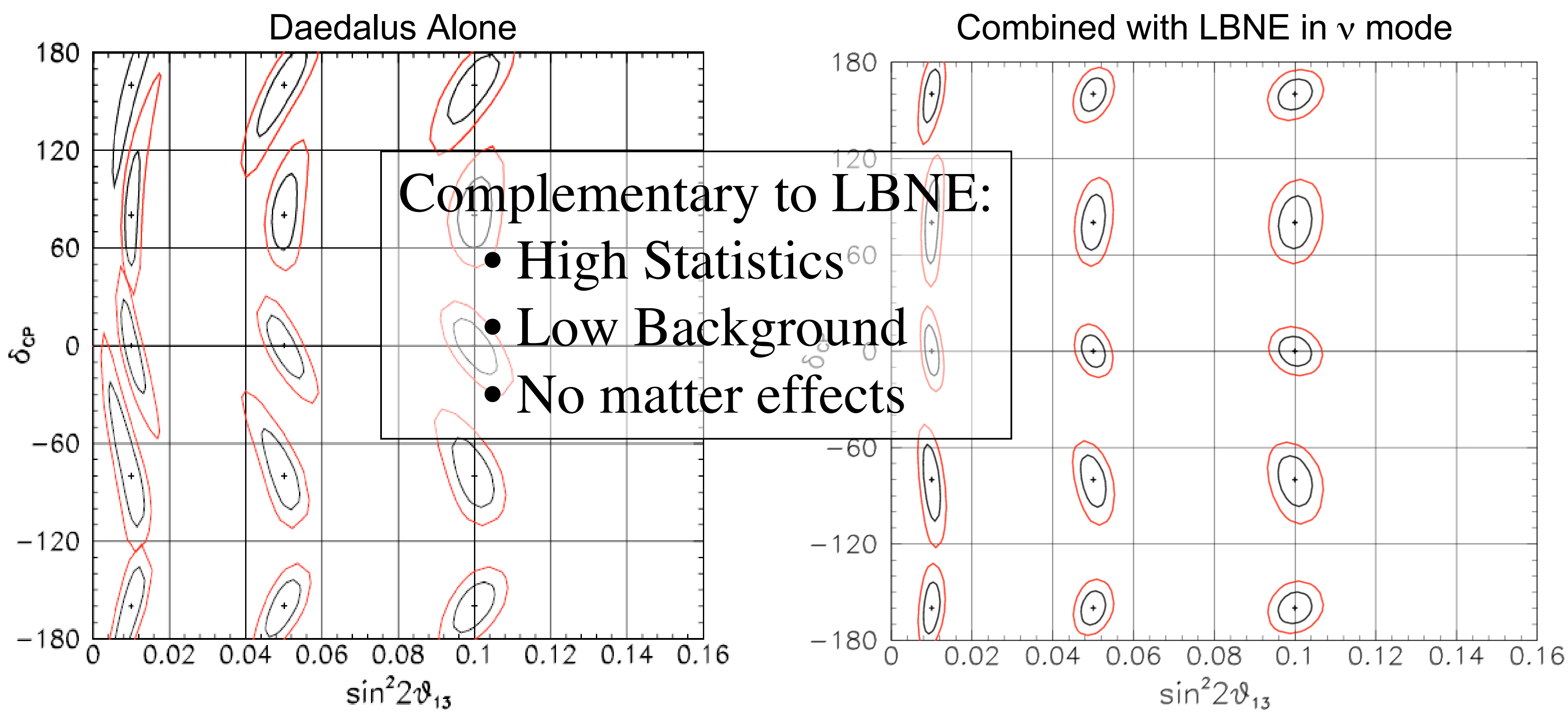
Outline:

1) The DAEδALUS idea -- CP violation
2) What do we want in a Neutrino Source
3) Cyclotrons to produce the proton beam
4) Non-oscillation SBL physics

Next --- Mike Shaevitz's talk: SBL Oscillations

# DAEδALUS

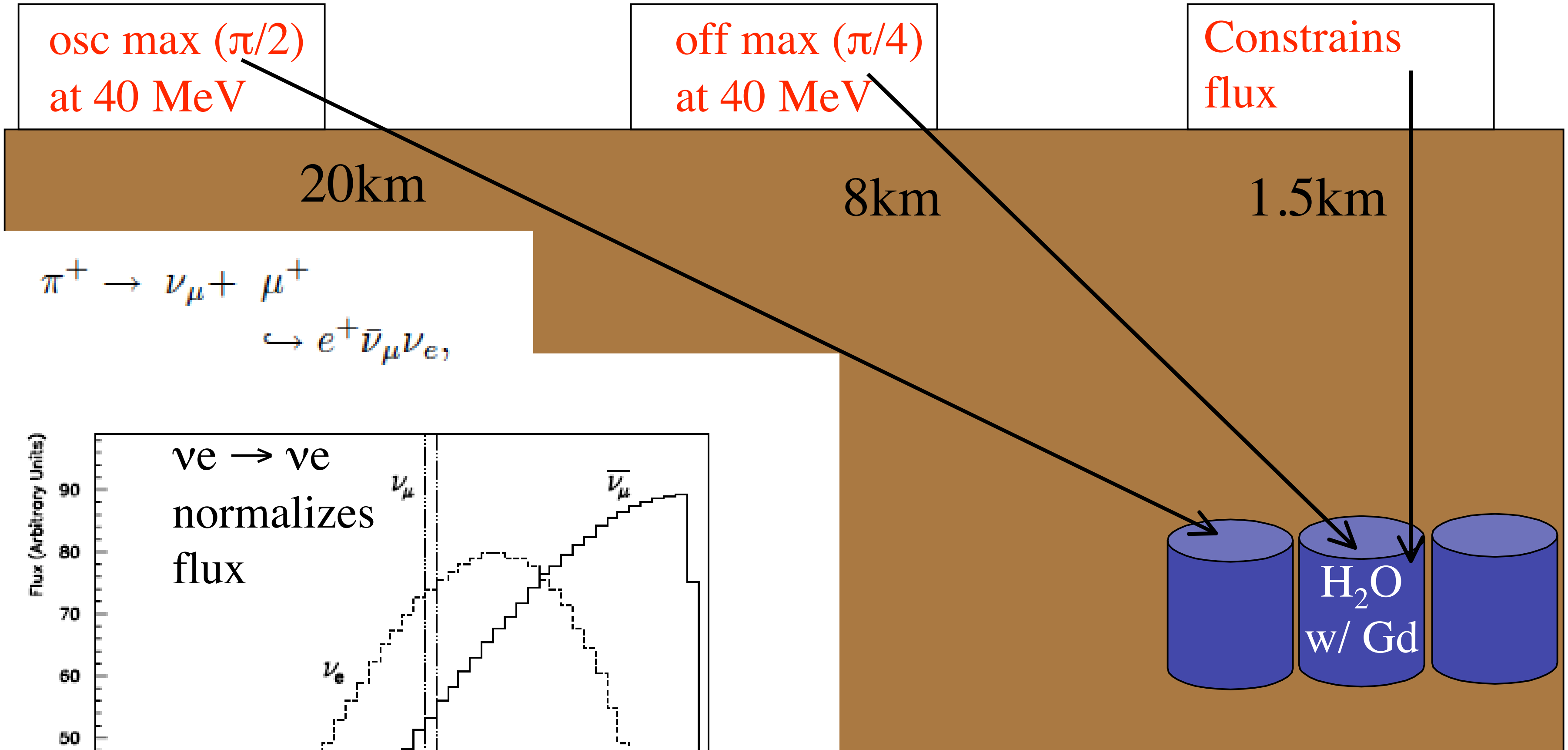
A $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ search, exploiting the L/E dependence of the CP-interference term to extract $\delta$



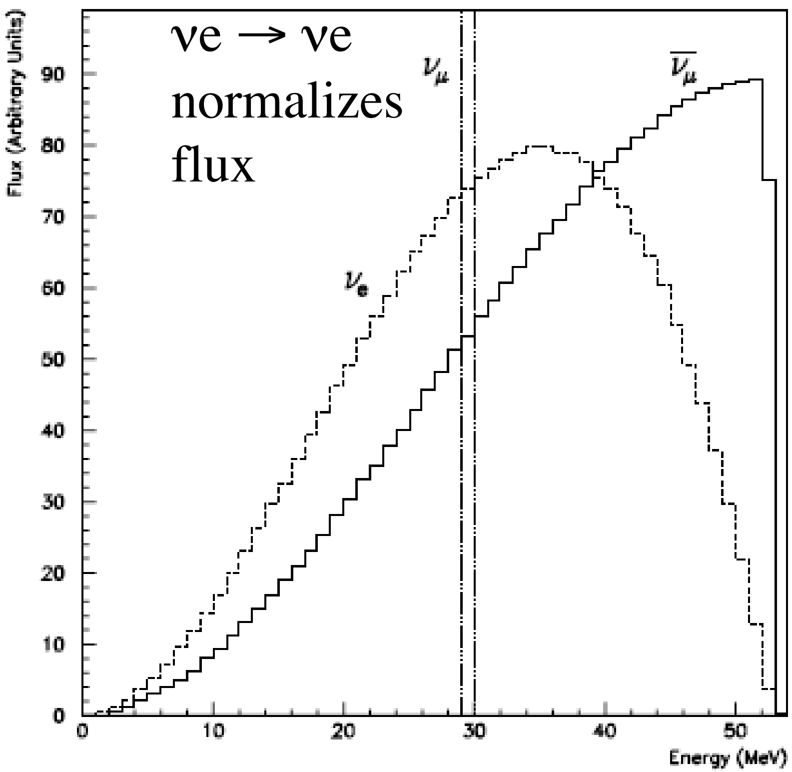

Complementary to LBNE:

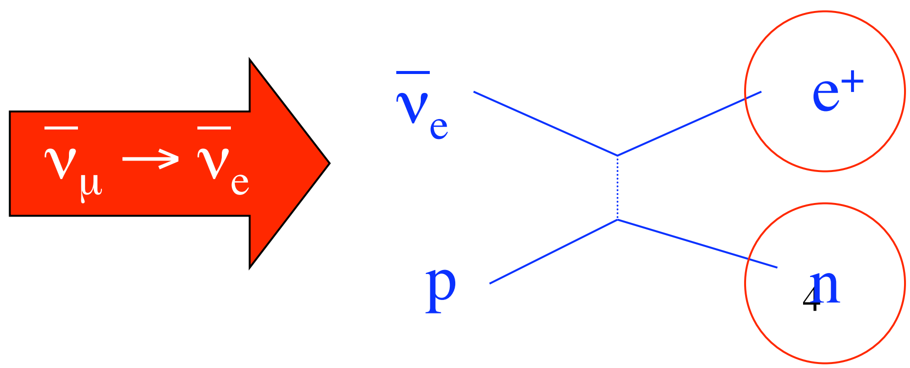
- High Statistics
- Low Background
- No matter effects

# A multiple-baseline, single-detector experiment




$$\pi^+ \rightarrow \nu_\mu + \mu^+$$
$$\hookrightarrow e^+ \bar{\nu}_\mu \nu_e,$$



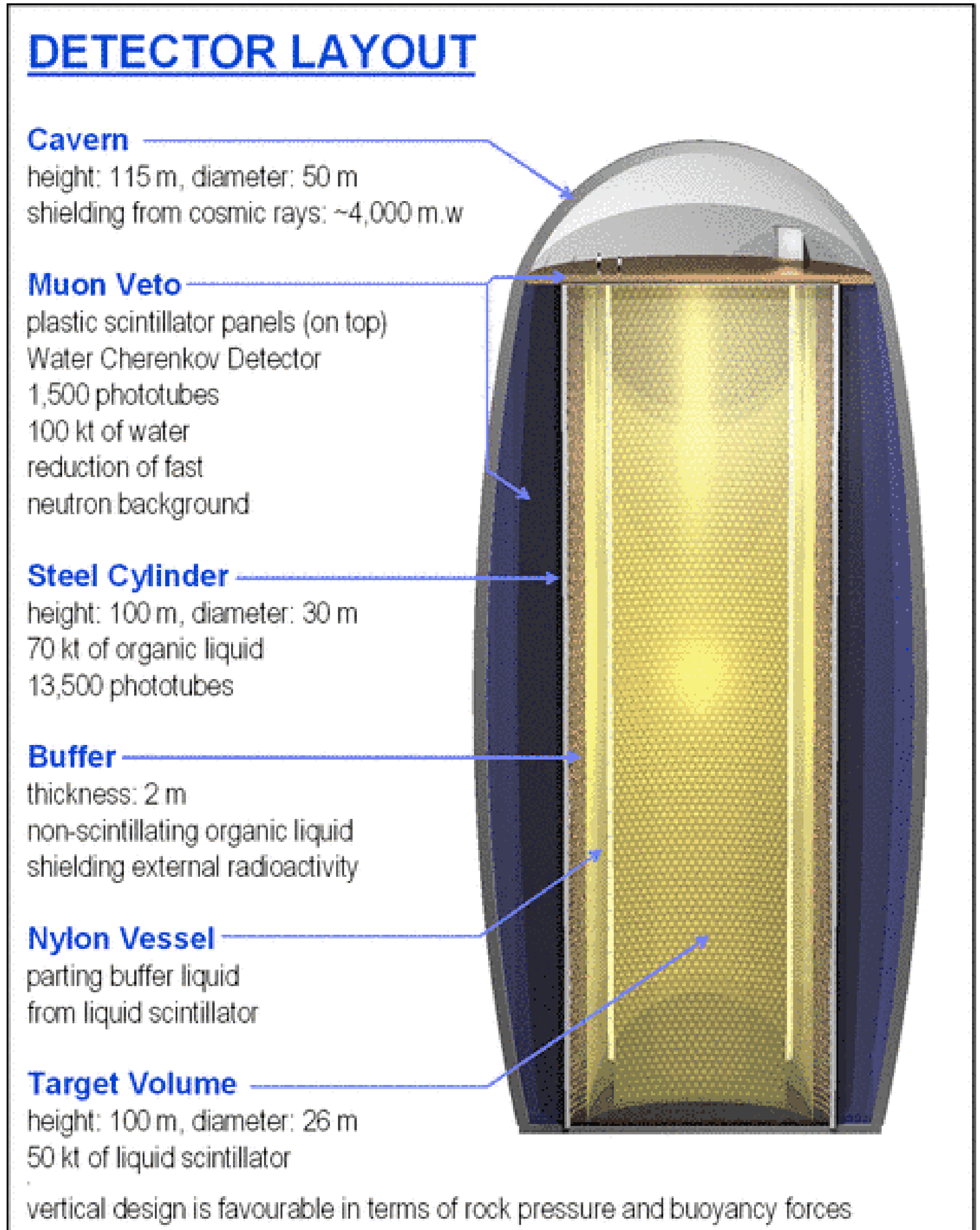



SITE OPTIONS:

Large water detectors:
LBNE
MEMPHYS
Hyper-K

Or scintillation oil
-based detectors:
LENA, Hano-Hano
arxiv:1104.5620

For now I use H2O
as my example…



Measurement strategy:

Using **near accelerator**
measure **absolute flux normalization** with $\nu$-e events to ~1%,
Also, measure the $\nu_e$O event rate.

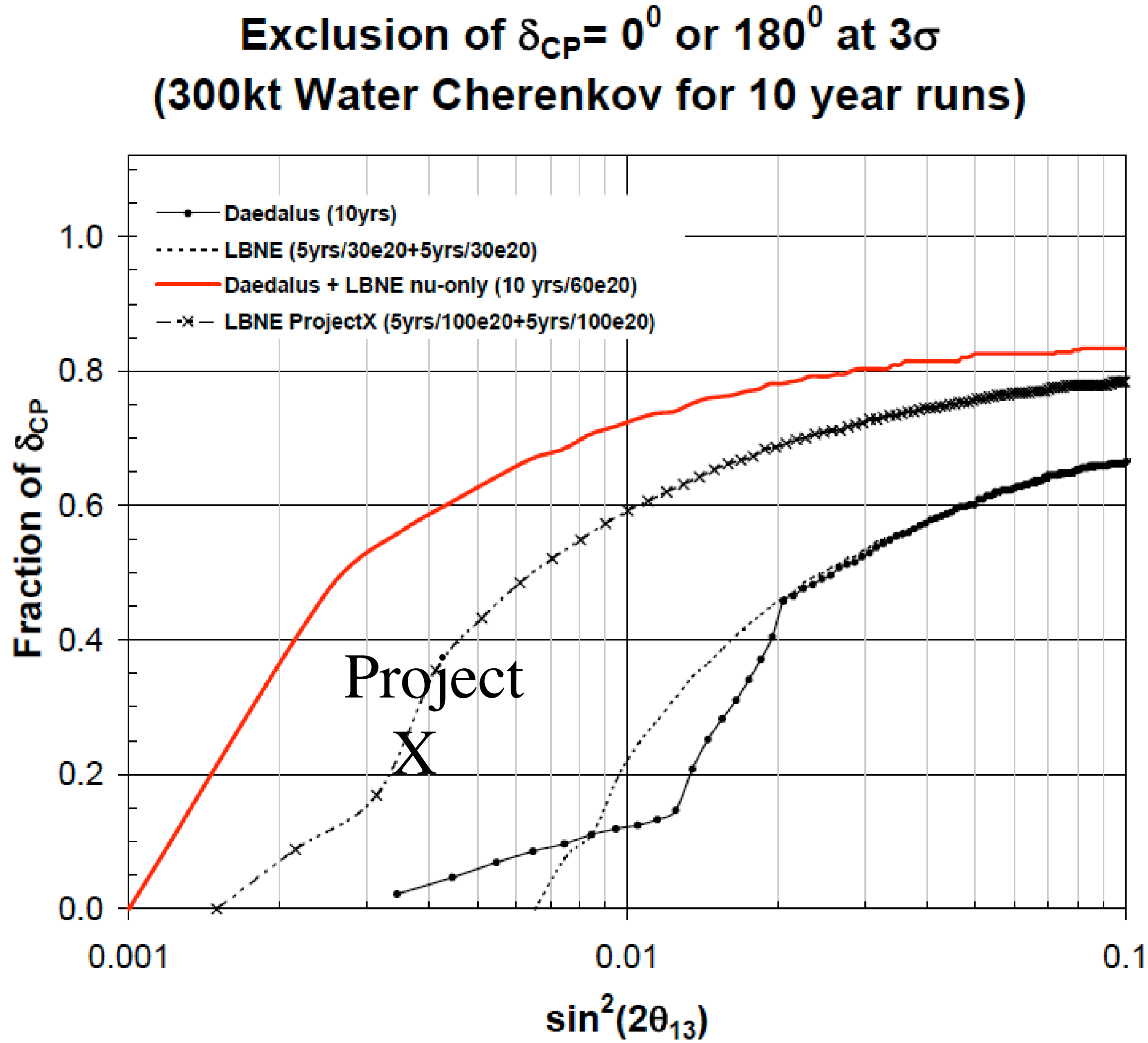
↓

At far and mid accelerator,
Compare predicted to measured $\nu_e$O event rates
to get the **relative flux normalizations between 3 accelerators**

↓

In all three accelerators,
given the known flux, **fit for the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal**
with free parameters: $\boldsymbol{\theta_{13}}$ **and** $\boldsymbol{\delta}$

The fraction of “δ-space” where a measurement will be >3σ



## Papers:

*Expression of Interest: arXiv:1006.0260*

see also…

- Multiple Cyclotron Method to Search for CP Violation in the Neutrino Sector, arXiv:0912.4079, Phys. Rev. Lett. 104, 141802 (2010)
- A Study of Detector Configurations for the DUSEL CP Violation Searches Combining LBNE and DAEdALUS, arXiv:1008.4967
- The DAEδALUS Project: Rationale and Beam Requirements, arXiv:1010.0971
- A Multi Megawatt Cyclotron Complex to Search for CP Violation in the Neutrino Sector, arXiv:1010.1493, arxiv:1104.4985

# DAEδALUS

The Neutrino Source

What do we want? A very pure DAR beam

1) Produce a lot of $\pi+$
2) While minimizing all other particles!
   $\pi-$, kaons, neutrons…
3) Kill off $\pi-$ by capture $\Rightarrow$ reduce DIF!
4) Minimize source size compared to $L_{osc}$

Note that our original paper suggested 2 GeV p.o.t.
We have learned that this energy is a poor choice -- too high!
800 MeV is the best choice.

# Production data on p+Be target…

(collected in MB technote by Shaevitz)

| | Produced Hadron | Exclusive Reaction | $M_X$ $(GeV/c^2)$ | $\sqrt{s_{thresh}}$ (GeV) | $E^{beam}_{thresh}$ GeV | KE of beam (MeV) |
|---|---|---|---|---|---|---|
| wanted | $\pi^+$ | $pn\pi^+$ | 1.878 | 2.018 | 1.233 | 295 |
| Not wanted | $\pi^-$ | $pp\pi^+\pi^-$ | 2.016 | 2.156 | 1.54 | 602 |
| | $\pi^0$ | $pp\pi^0$ | 1.876 | 2.011 | 1.218 | 280 |
| | $K^+$ | $\Lambda^0 pK^+$ | 2.053 | 2.547 | 2.52 | 1582 |
| | $K^-$ | $ppK^+K^-$ | 2.37 | 2.864 | 3.434 | 2496 |
| | $K^0$ | $p\Sigma^+K^0$ | 2.13 | 2.628 | 2.743 | 1805 |

We want to be well above threshold to produce a lot of π+ but near or below threshold to produce very little π– and no kaons!

800 MeV will be a good choice…

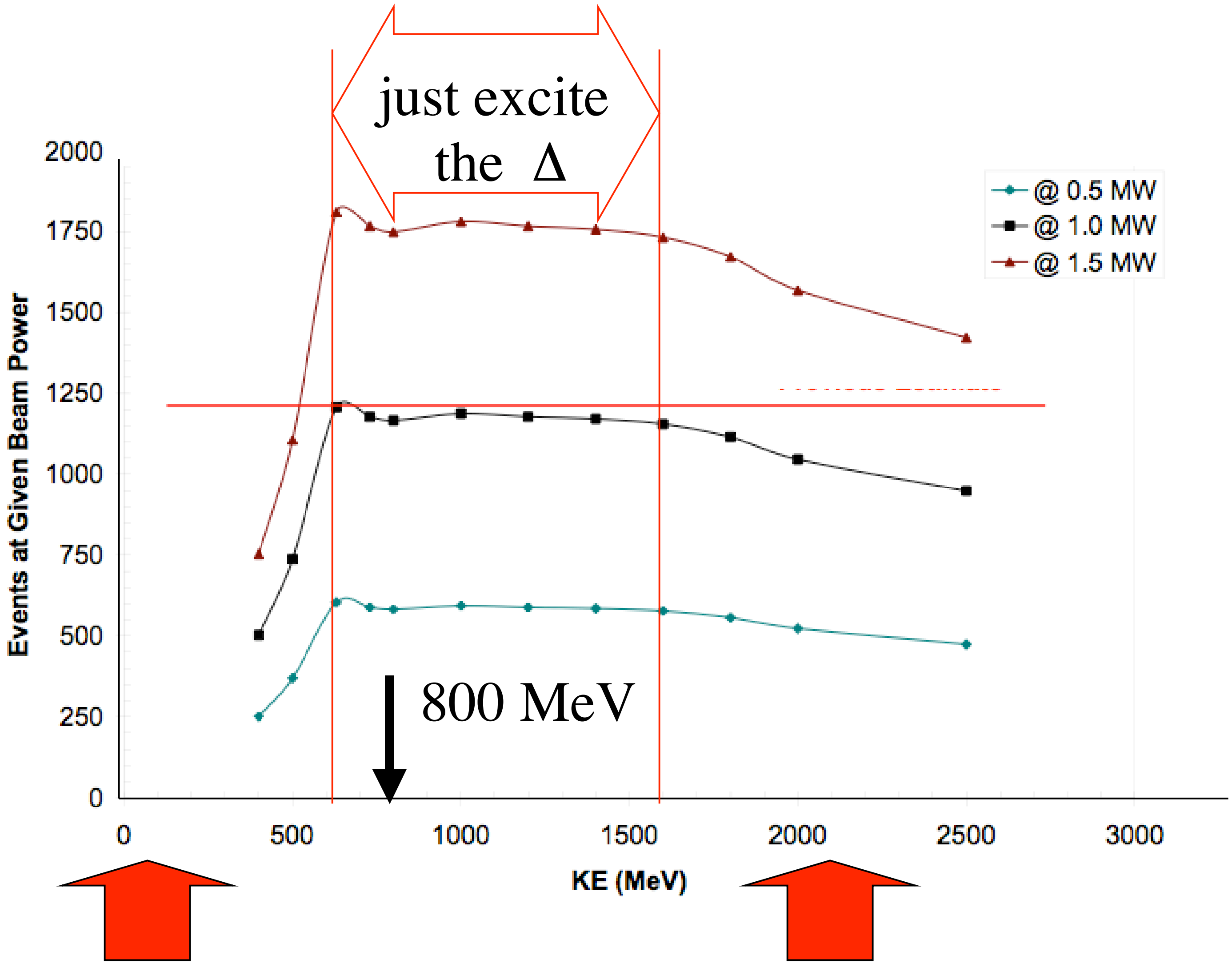
## Production data on p+Be target…

(collected in MB technote by Shaevitz)

| Produced Hadron | Exclusive Reaction | $M_X$ $(GeV/c^2)$ | $\sqrt{s_{thresh}}$ (GeV) | $E^{beam}_{thresh}$ GeV | KE of beam (MeV) |
|---|---|---|---|---|---|
| wanted $\pi^+$ | $pn\pi^+$ | 1.878 | 2.018 | 1.233 | 295 |
| $\pi^-$ | $pp\pi^+\pi^-$ | 2.016 | 2.156 | 1.54 | 602 |
| $\pi^0$ | $pp\pi^0$ | 1.876 | 2.011 | 1.218 | 280 |
| $K^+$ | $\Lambda^0 p K^+$ | 2.053 | 2.547 | 2.52 | 1582 |
| $K^-$ | $ppK^+K^-$ | 2.37 | 2.864 | 3.434 | 2496 |
| $K^0$ | $p\Sigma^+K^0$ | 2.13 | 2.628 | 2.743 | 1805 |

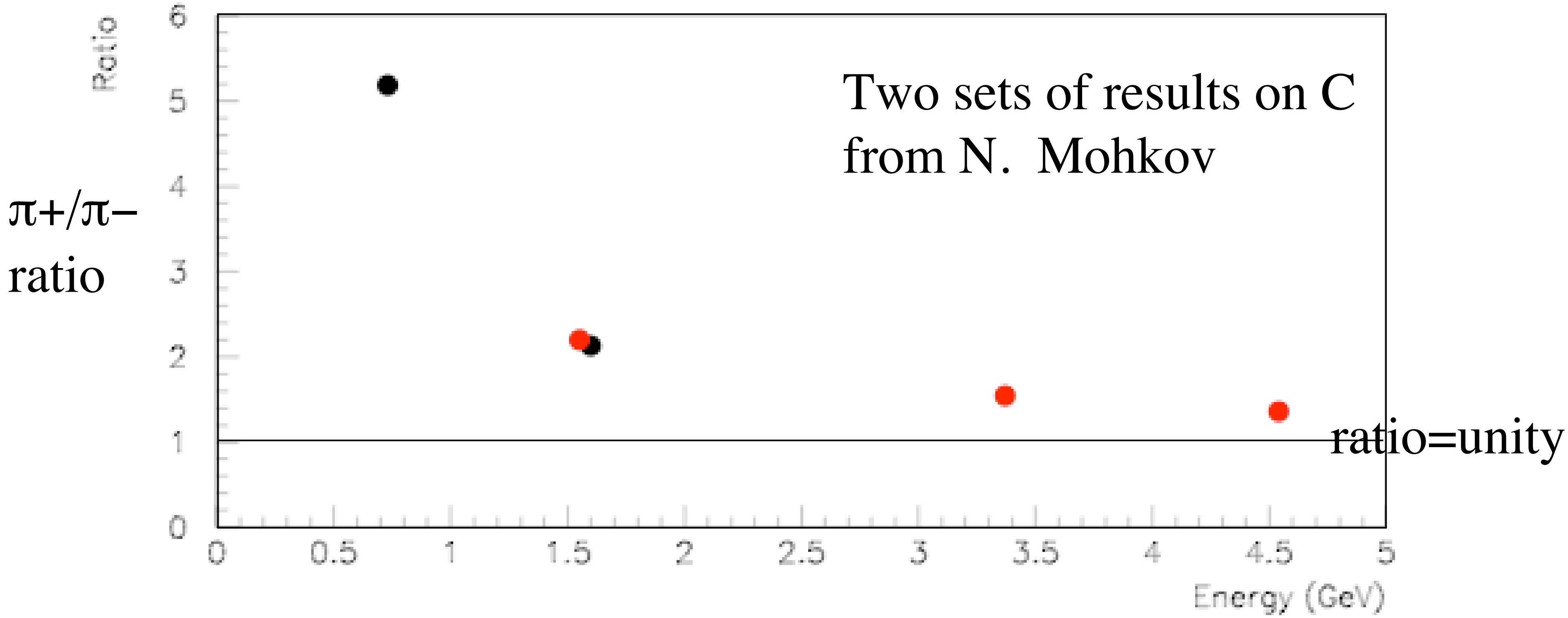
Kaons are especially problematic because once produced, they do not capture, like the π– …they stop and decay. The π/K ratio is not well understood -- hard to predict

Avoid Energies >1500 MeV




not enough energy
to excite the Δ resonance

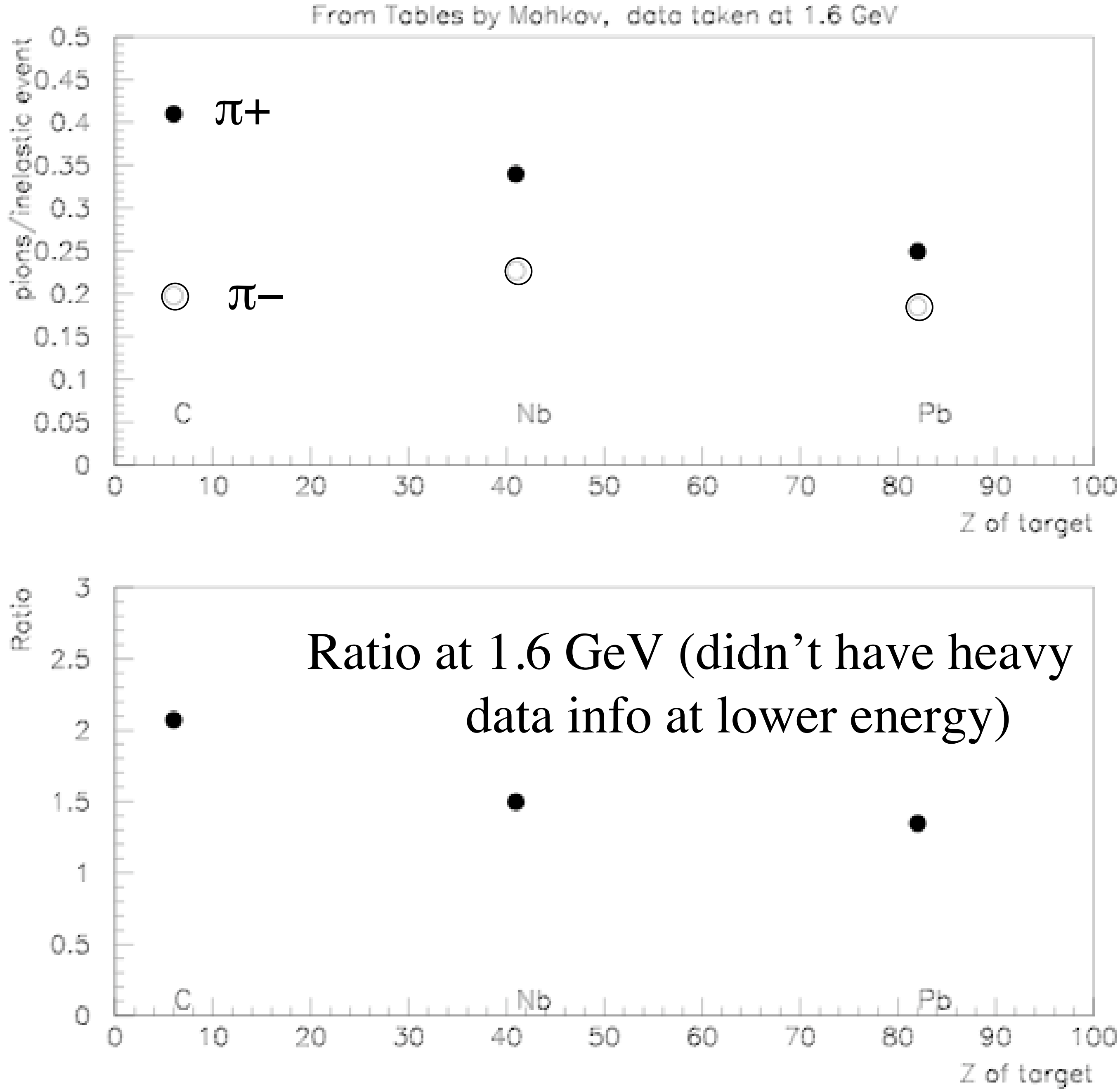
Energy goes into other
processes, not just DAR:
> 1500 MeV is not efficient.




800 MeV is close enough to the π− production threshold
to strongly suppress production!

> 1500 MeV --  production ratios close to unity

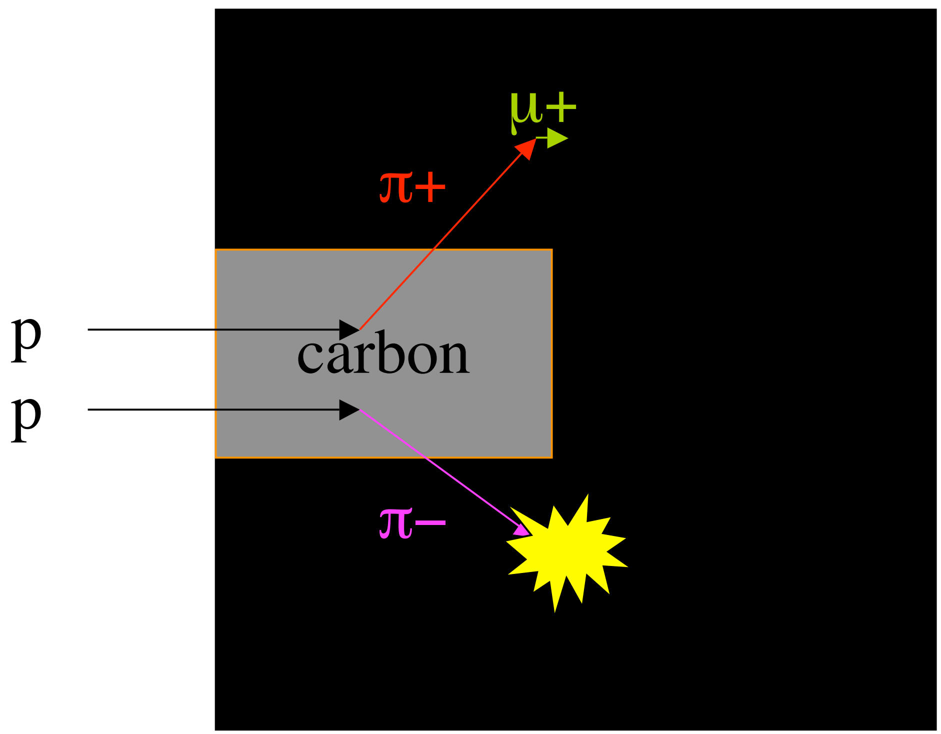
Lighter targets are better



Remove the $\pi-$ that are produced -- Minimize DIF

- $\pi-$ capture when they stop
- all flavors of DIF neutrinos are a problem because they do not have a well defined spectrum

Solution: Light target embedded in a heavy target




Also,
no upstream
targets!!!

## Minimize neutron production

- wastes beam energy
- increases $\pi^-$ background
  (if p knocks out n, n can produce $\Delta^0 \rightarrow \pi^- p$)
- makes shielding for neutron backgrounds easier.

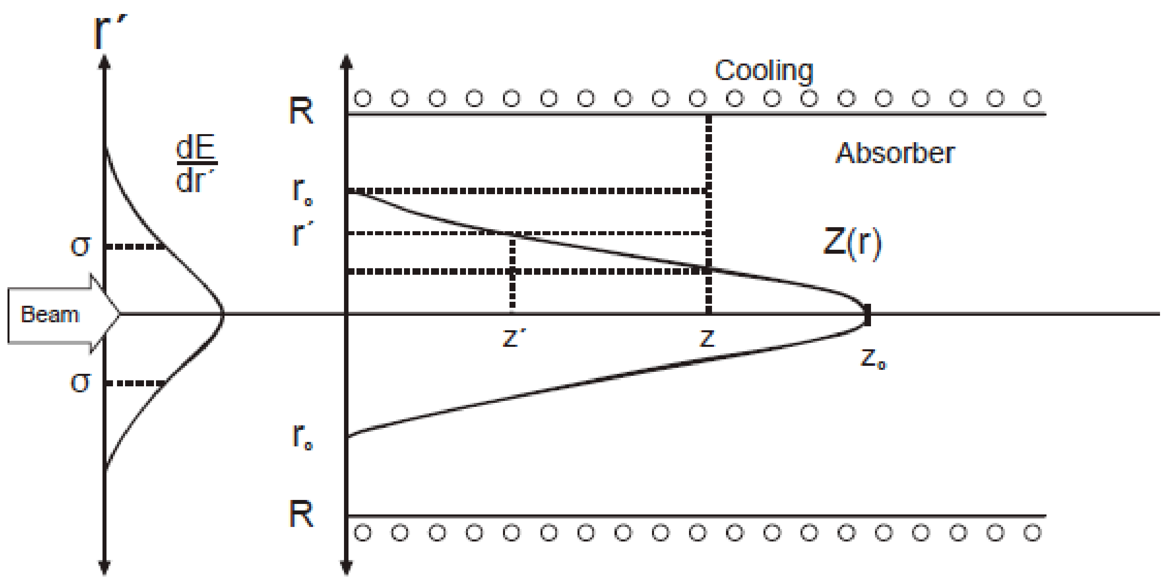
Solutions: Use a light target (C, $H_2O$)
Use a lot of shielding to absorb n's

*Note that spallation sources produce neutrons on purpose, so they are not very efficient neutrino sources!*

## A source size which is small vs osc. wavelength

The size of the neutrino production region depends on…

1) Number of times an incoming proton will interact to produce a $\pi+$ (length ~25 cm)
2) stopping length of the $\pi+$ (length ~10 cm)
3) tapering introduced to spread the beam across the target




total smearing will be <50 cm for DAR

# DAEδALUS

## The Accelerators

Wanted: ~1 MW sources of protons,
w/ energy ~800 MeV for a reasonable price

What helps:

1. No fancy beam structure -- CW is fine.
   (run 100 ms on and 400 ms off for CP violation, running longer periods may be fine for sbl)

2. No need to inject into another accelerator

3. Constant energy -- no need for an energy upgrade path

… Unlike Project-X or SNS,
which need the above

Luckily there are others looking for ~1 GeV Machines!

"ADS" -- accelerator driven systems for subcritical reactors.

"DTRA"-- Defense Threat Reduction Agency

Both applications & others are of interest to industry…

## Among all of the types of accelerators out there…

Cyclotrons
Synchrotrons
Linacs
FFAGs
etc.

**Why cyclotrons?**

Inexpensive,
Only practical below ~1 GeV
(ok for us!)
Only good if you don't need
timing structure (ok!)
Typically single-energy (ok!)
**Taps into existing industry**

Very interesting R&D ongoing, but these machines are not yet proven

Can do what we need right now, but are expensive.

Use linacs if you want a nice beam for transfer to another line and flexibility on energy (We don't)

*We do not rule out other options, but cyclotrons seem like a good fit.*

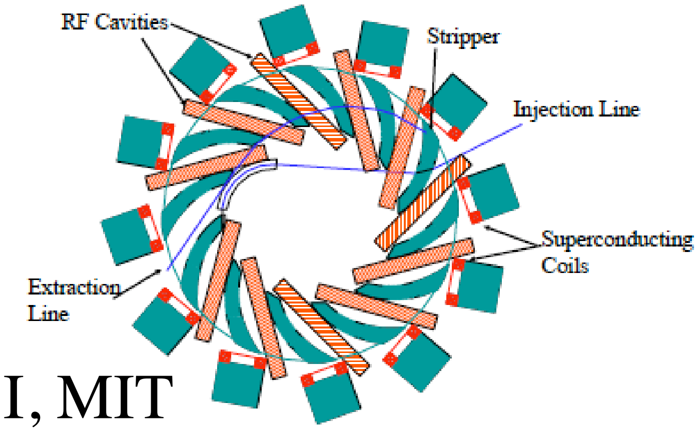
Approaches using cyclotrons:

The compact cyclotron with self-extraction

under development for DTRA at MIT

An H2+ accelerator

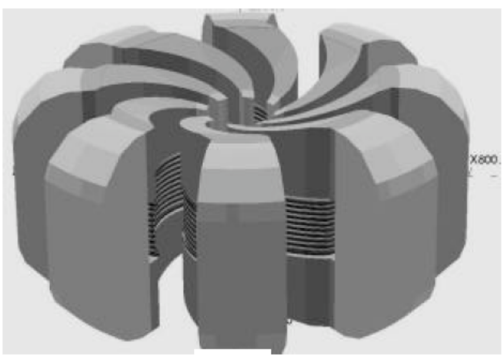
for ADS applications




Under dev. by INFN, PSI, MIT Cockcroft Inst.

The stacked cyclotron:

7 cyclotrons in one flux return

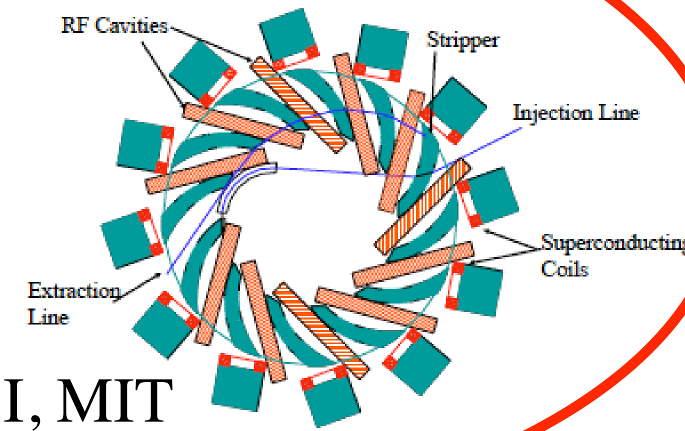


Under dev. for ADS at TAMU

An H2+ accelerator

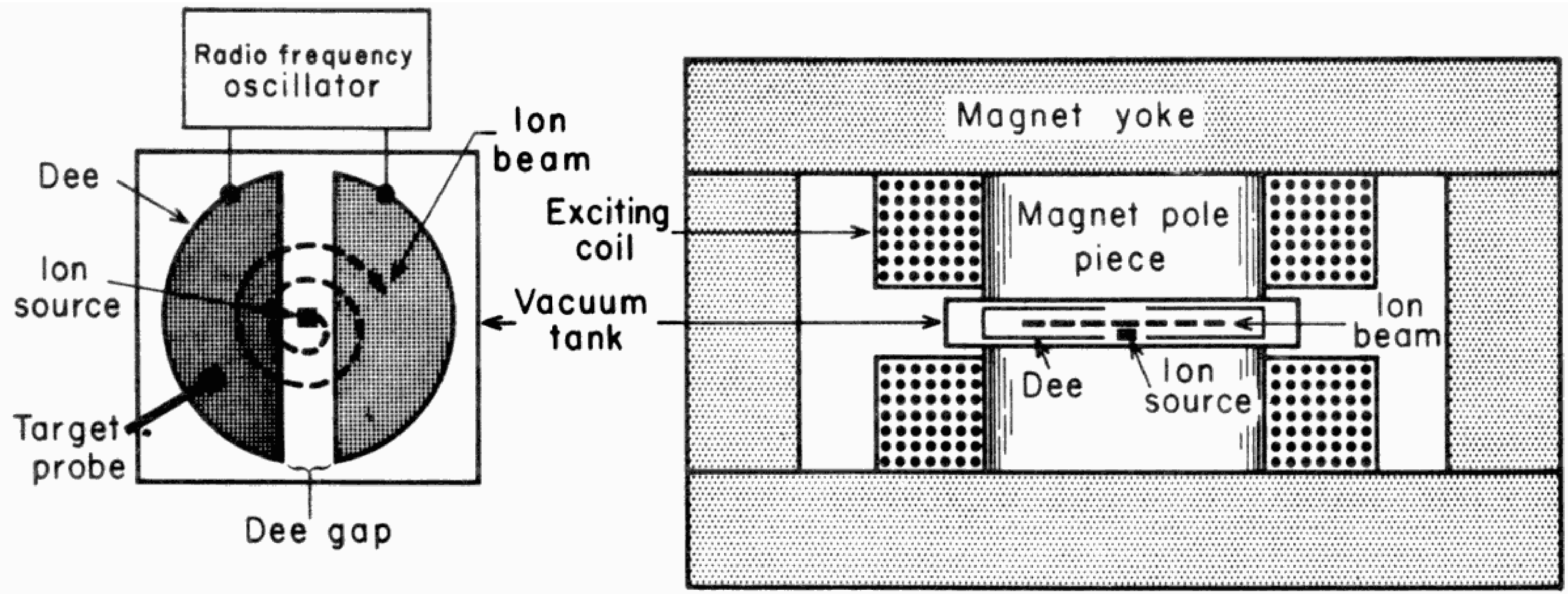
for ADS
applications

Under dev.
by INFN, PSI, MIT
Cockcroft Inst



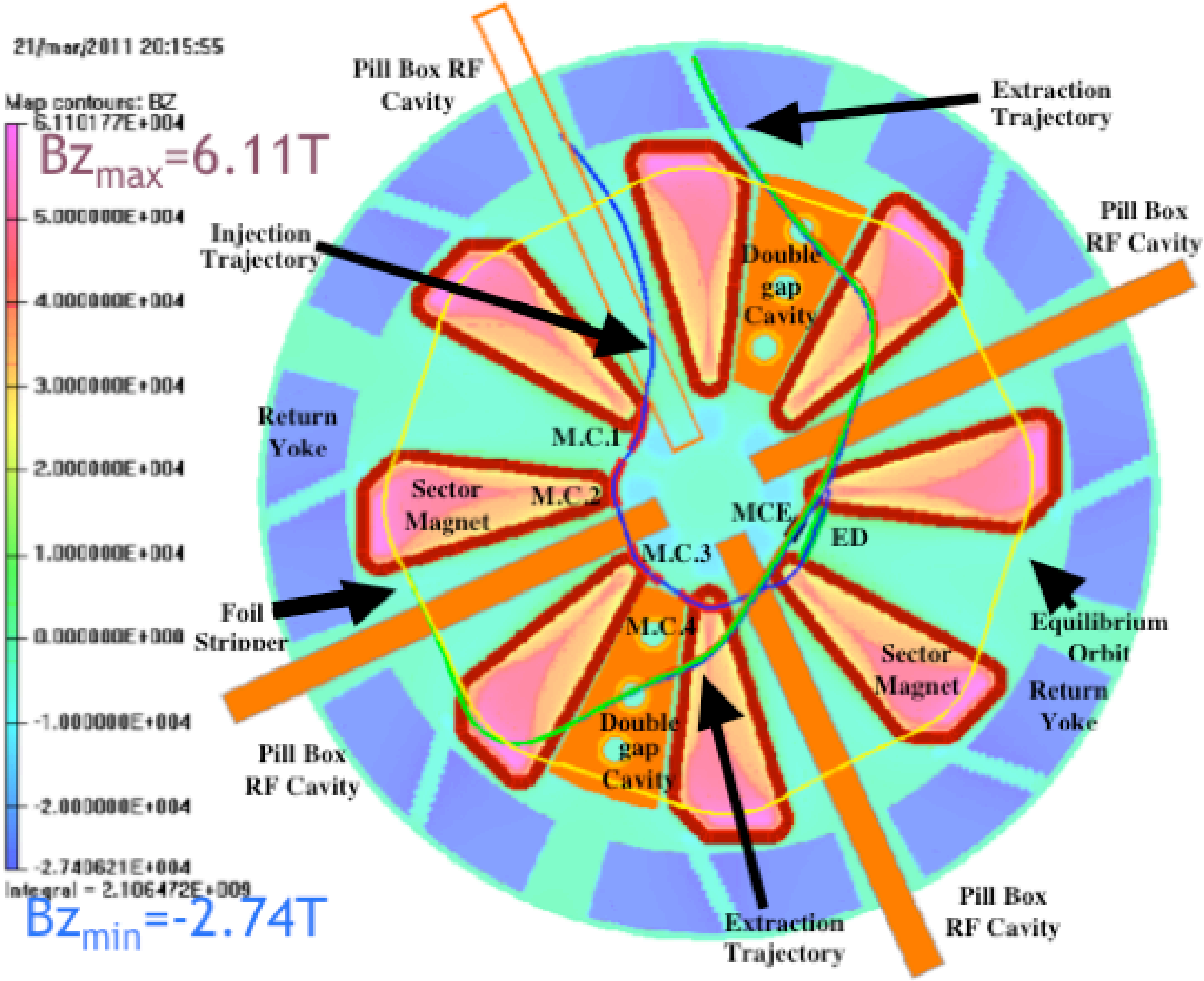

The example design I will describe today

# Cyclotrons 101



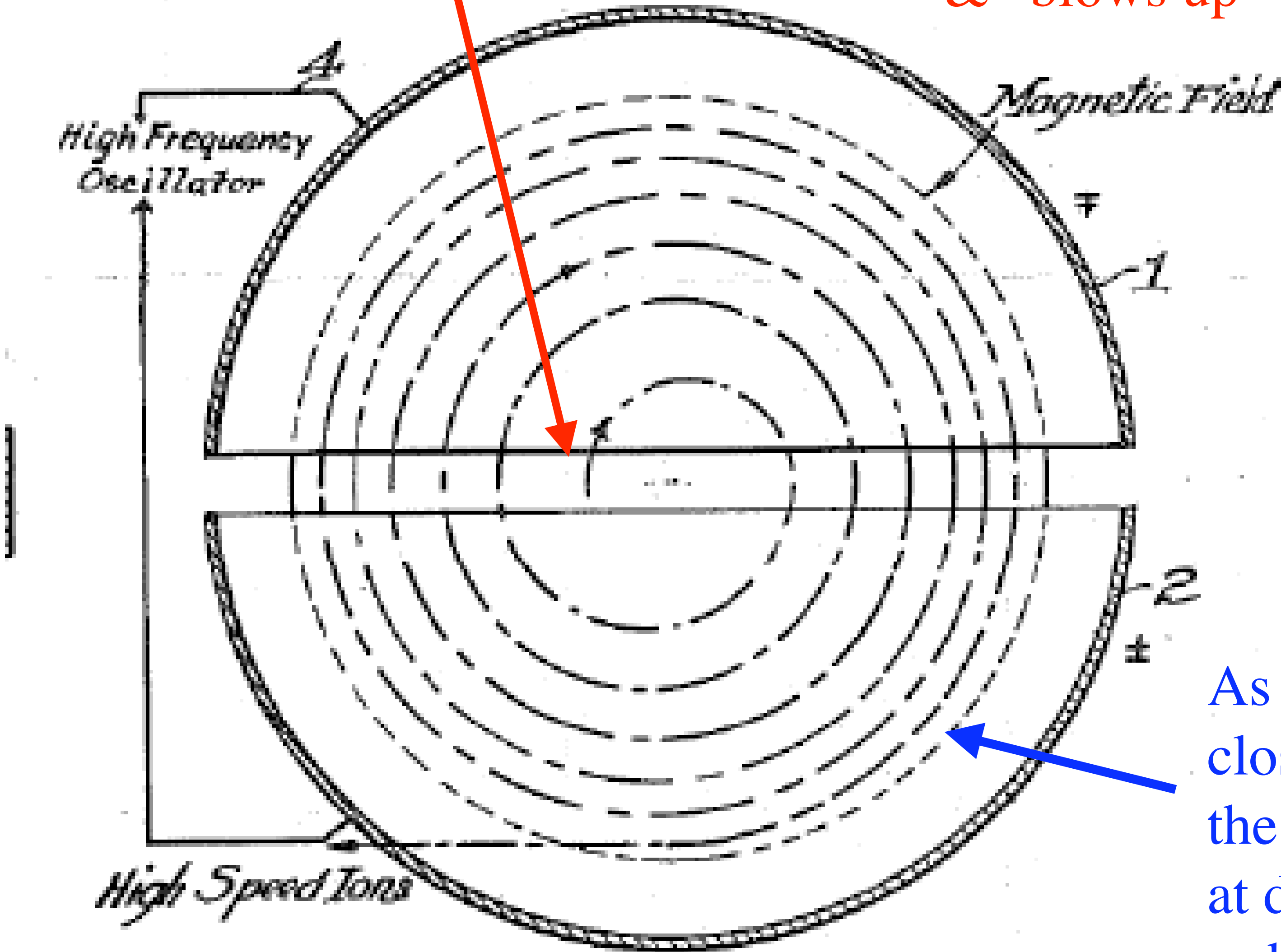

We employ an "isochronous cyclotron" design where the magnetic field changes with radius, but RF does not change with time.
This can accelerate many bunches at once.

# Our magnet design



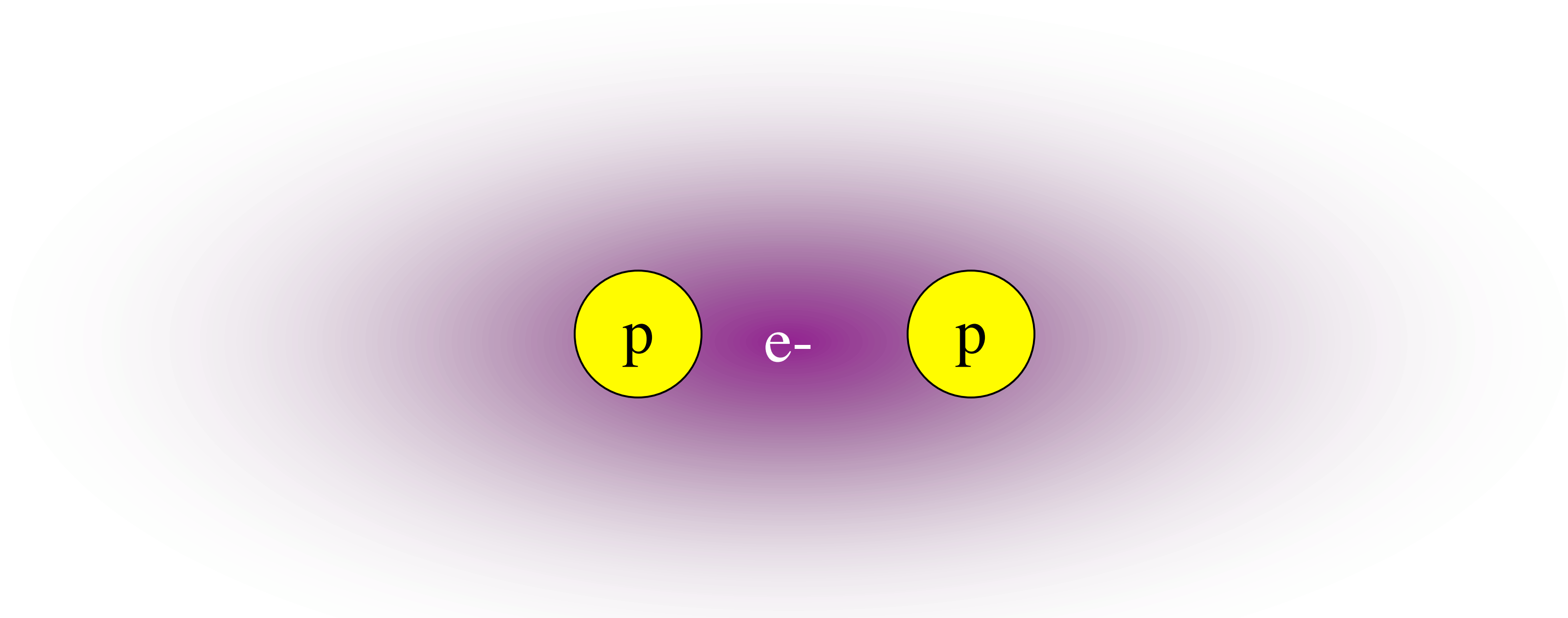
The big issue…

If you inject a lot of charge here, it repells & “blows up”




As radii get closer together the bunches at different radii interact

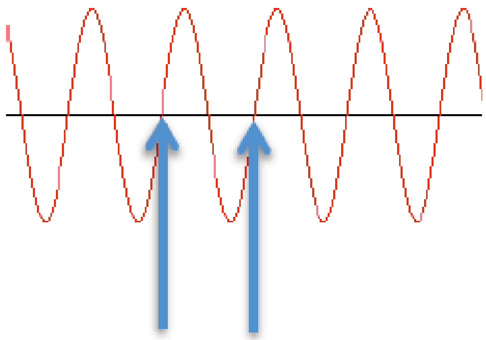
We need to reduce "space charge" at the start…




$H_2^+$ gives you 2 protons out for 1 unit of +1 charge in!

Simple to extract! Just strip the electron w/ a foil

## An important point about beam structure…



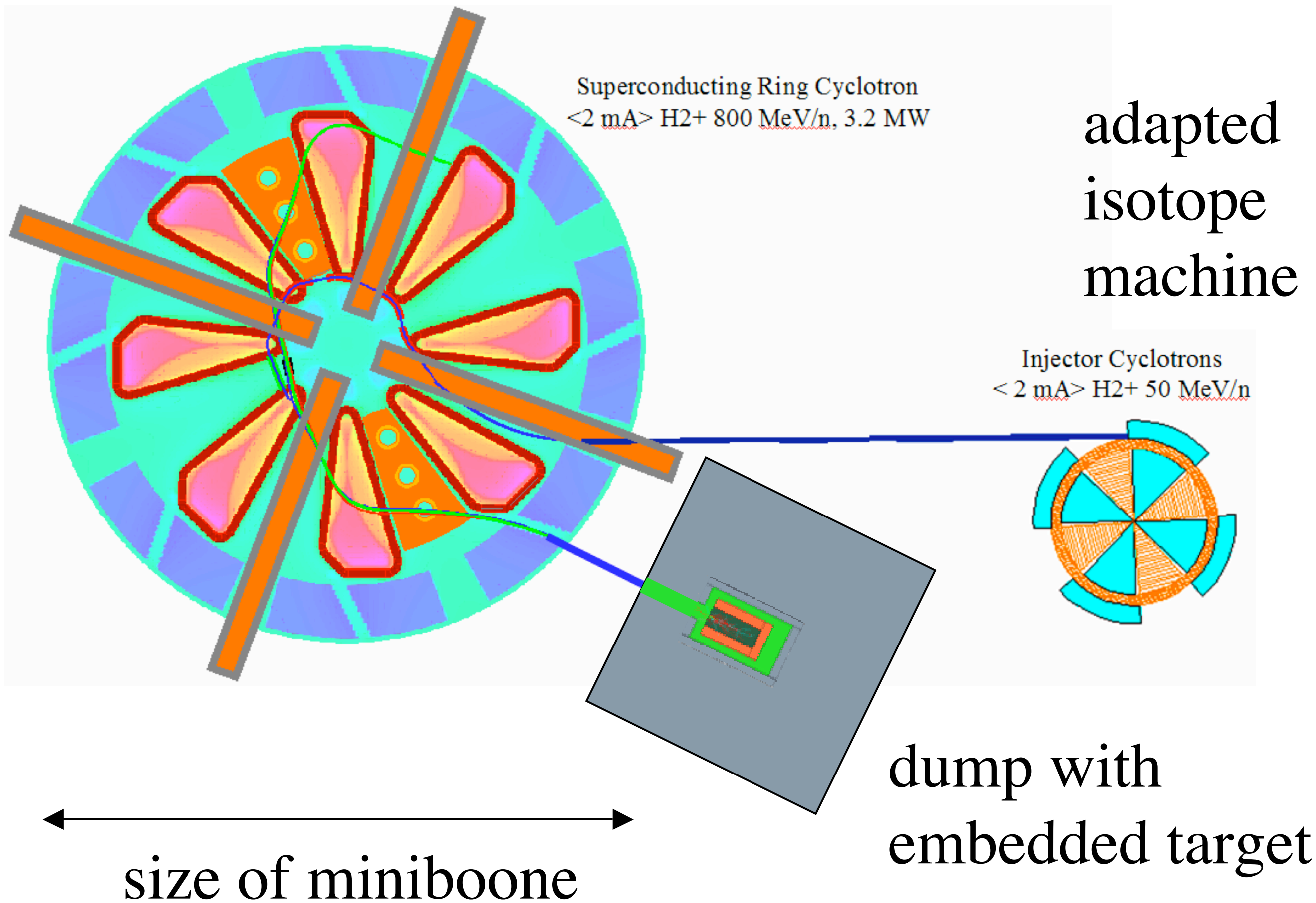
66 MHz
15.15 ns

Tiny compared to the microsecond time structure of μ decay.

You can turn cyclotrons on/off, but only on millisecond (or larger) scales.

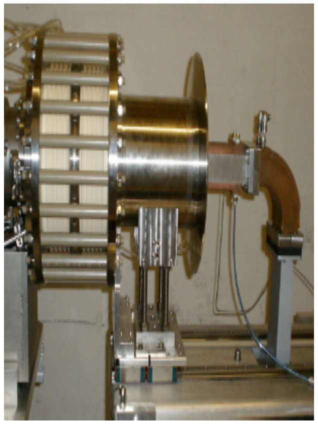
This beam is effectively continuous

You cannot use beam timing to differentiate flavors, as was proposed for OscSNS




It is relatively easy to site this anywhere that interesting detectors are built.

Components are based on working examples,
Now we need to optimize for our purposes.



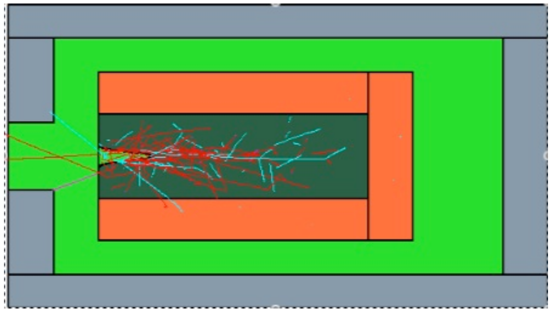
The ion source: prototype built at Catania

The injector cyclotron: modest modification to off-shelf model from, *e.g.*, BEST Cyclotron Systems Inc.

The main cyclotron: smaller, simpler version of Riken (Japan)

The extraction foils: well tested at many cyclotron facilities, including PSI and TRIUMF

The target/dumps: We can have multiple extraction lines for < 1 MW on target (in keeping with existing dumps), but higher power designs are presently under study



MARS target/dump simulations underway

Some highlights of progress & plans

- We have a 1st generation design

- We have a prototype ion source, which produced 20 mA immediately

- The large magnet specifications are nearly complete, and we expect to go to engineers for costing within 6 months. This is the cost driver.

*The above was reported at the*
*Particle Accelerator Conference a month ago.*

arxiv:1104.4985

# DAEδALUS

## Non-Oscillation Physics

# Non-oscillation Physics

## 1) Test/improve nuclear models

inclusive $^{12}C \rightarrow {}^{12}N_{gs}$

| | $(\nu_e, e^-)$DAR $\langle\sigma\rangle_f$, $10^{-42}$ cm$^2$ | |
|---|---|---|
| RPA | 49.47 | |
| QRPA | 42.92 | |
| CRPA [9] | 13.88(12.55) | |
| SM(HF wf) $(0+1+2)\hbar\omega$ | 8.11 | |
| SM(WS wf) $(0+1+2)\hbar\omega$ [10] | 8.4 | |
| Experiment | $10.5 \pm 1.0 \pm 1.0$ [22] | |
| | $9.1 \pm 0.4 \pm 0.9$ [23] | LSND |
| | $9.1 \pm 0.5 \pm 0.8$ [24] | KARMEN |

*Physics of Atomic Nuclei, Vol. 64, No. 7, 2001, pp. 1165–1168.*

We only have data on C, H, Fe, I in 10 - 50 MeV range

## 2) Use the cross sections to study supernovae!

… but then we will need more cross sections!

Like Argon!

.. and water too

Calculations have big variations!

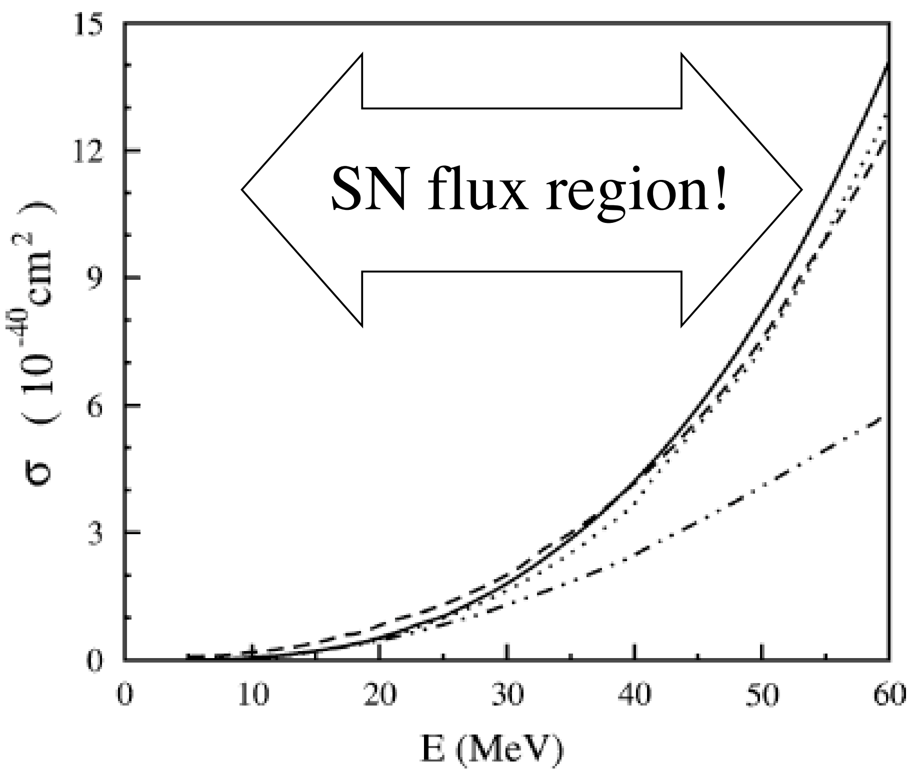



Fig. 3. Total cross section $\sigma$ vs. $E$ for $\nu_e + {}^{40}Ar \to e^- + {}^{40}K^*$ reaction with Fermi function (solid line), modified effective momentum approximation (dashed line), Ormand et al. [12] (dashed-double dotted line) and Bueno et al. [13] (dotted line).

*M.S. Athar, S.K. Singh / Physics Letters B 591 (2004) 69–75*

## 3) Use the Cross Sections for BSM physics

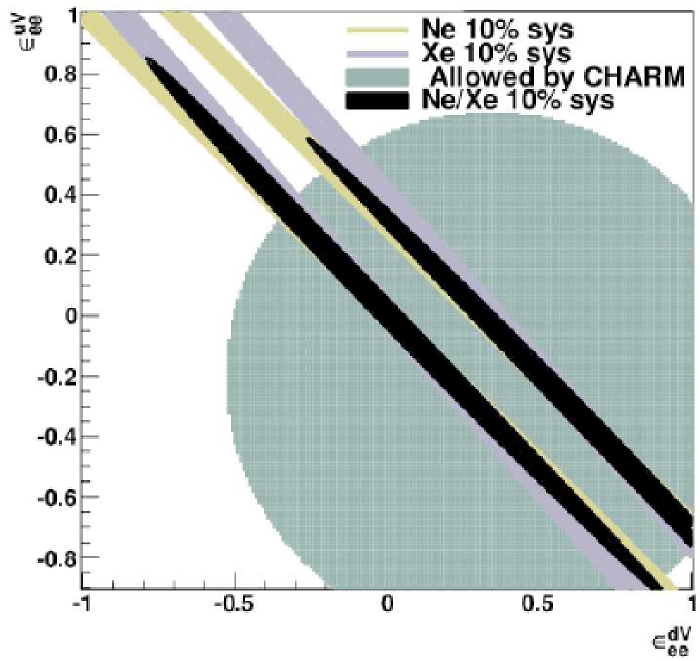
Coherent scattering has never been measured,
DAR beams are wonderful for this.

http://arxiv.org/abs/hep-ex/0511042
Kate Scholberg

http://arxiv.org/abs/1103.4894
Josh Spitz, Tali Figueroa, et al

Interesting tests of SM, including nonstandard couplings…

Re-use Dark Matter designs!
CLEAN/CLEAR
GEODM



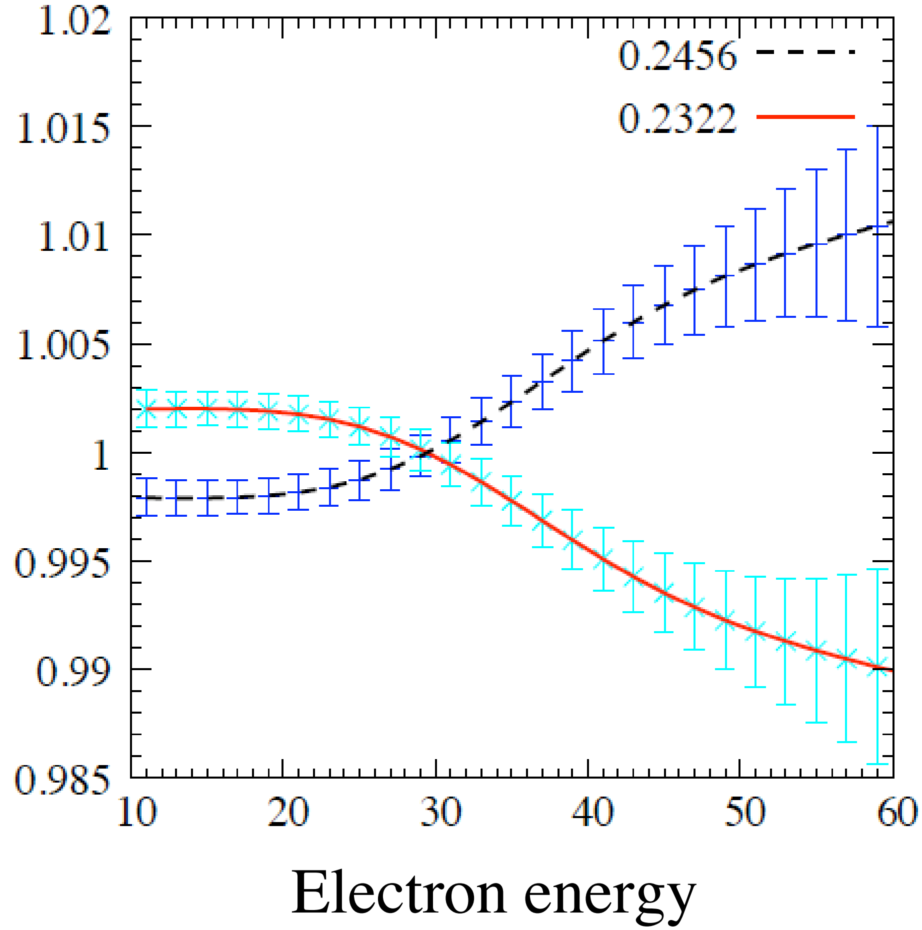

| GEODM Module Close to the $\nu$ Source Assumptions | |
|---|---|
| Scenario considered | "Optimistic" |
| Source | $4 \times 10^{22}$ $\nu$/flavor/year w/ 13% duty factor |
| $\nu$ flux uncertainty | 2% |
| Distance from $\nu$ source | 20 m |
| Exposure | 50 kg-year |
| Background rate | 0.1 events/(10 kg-day) in beam window |

1350 events with a 50 kg.yr exposure!

## … another example: Precision $\sin^2 \theta_W$

Neutrino-electron scattering rates

$$\frac{\text{Measured}}{\text{Predicted}}$$




For a DAEδALUS cyclotron 60 m from 300 kt at DUSEL

argawalla & huber, http://arxiv.org/abs/1005.1254

More examples -- already presented at the workshop, including

* Lorentz violation has a very distinct signature,
see talk by Jorge Diaz

* The search for new light states is ideal for DAEδALUS
see talk by Roni Harnik

… We can develop a very rich SBL program,
well beyond the beautiful oscillation studies
that Mike Shaevitz will present (next talk)

# Quality of Measurement Depends on Knowledge of Flux

The first-principles flux prediction has ~10% error
due to the pion production cross sections

But if you believe in short-baseline oscillations,
then you need a flux correction!

And, anyway, you would like to do better…

Use neutrino electron scatter.
Best if in same detector,
but will have small error even in side-by-side

# DAEδALUS

Is motivated by CP violation

Requires high rate, low background DAR

Uses cyclotrons at ~ **800 MeV**

There are also exciting sbl uses like…

- cross section measurements
- short baseline oscillations

DAEδALUS offers a broad & exciting physics program!